The Production of Gamma Rays in the Galaxy

In this chapter we will briefly discuss four other mechanisms for galactic γ-ray production; viz, Compton interactions, bremsstrahlung, synchrotron radiation, and photomeson production. The results of these discussions, together with the results of chapters 5, 6, and 7, will then be summarized and applied to estimate γ-ray production spectra in various parts of the galaxy.

8–1 GAMMA-RAY PRODUCTION SPECTRA FROM COMPTON INTERACTIONS

The Compton effect has been treated extensively in the literature of high-energy astrophysics from three points of view: As an interaction in which cosmic-ray electrons lose energy (Feenberg and Primikoff, 1948, and Donahue, 1951; see also ch. 7); as an interaction in which γ-rays lose energy to electrons of thermal energy (e.g., see ch. 4); and as an interaction capable of producing high-energy γ-rays when thermal photons interact with cosmic-ray electrons. This last process, which we will now briefly discuss, has long been considered to be a potentially important source of cosmic γ-rays, first by interactions with starlight photons (Feenberg and Primikoff, 1948; Felten and Morrison, 1963) and later by interactions with the universal blackbody radiation (Felten, 1965; Gould, 1965; Hoyle, 1965; Fazio, Stecker, and Wright, 1966; and Felten and Morrison, 1966). The Compton process is the relativistic form of Thompson scattering. It is the scattering of a photon off an electron. Such a scattering is shown in figure 8–1 in both the laboratory frame and the rest frame of a cosmic-ray electron (Felten, 1966). We will use Felten's notation, with quantities in the electron rest system primed and laboratory quantities unprimed. Quantities referred to before the interaction will have no subscript and those referred to after the interaction will have the subscript 1. The cosmic-ray electron in the ls is assumed to have an energy $E=\gamma mc^2$. Using the formulas derived in

chapter 1 and referring to figure 8–1, we find

$$\epsilon' = \gamma\epsilon(1 + \beta \cos \alpha) \tag{8–1}$$

$$\epsilon_1 = \gamma\epsilon_1'(1 - \beta \cos \alpha_1') \tag{8–2}$$

$$\epsilon_1' = \frac{\epsilon'}{1 + \dfrac{\epsilon'}{mc^2}(1 - \cos \theta')} \tag{8–3}$$

and

$$\tan \alpha' = \frac{\sin \alpha}{\gamma(\cos \alpha + \beta)} \tag{8–4}$$

Combining equations (8–1) through (8–3), we then find

$$\epsilon_1 = \frac{\gamma^2\epsilon(1 + \beta \cos \alpha)(1 - \beta \cos \alpha_1')}{1 + \dfrac{\gamma\epsilon}{mc^2}(1 + \beta \cos \alpha)(1 - \cos \theta')} \tag{8–5}$$

For the applications of principal concern here, we will have the condition $\gamma\epsilon \ll mc^2$, so that the Compton cross section (Heitler, 1960)

$$\sigma_c \rightarrow \sigma_T = \frac{8}{3}\pi r_0^2 = 6.65 \times 10^{-25} \text{ cm}^2 \tag{8–6}$$

and, from equation (8–5),

$$\epsilon_1 \sim \gamma^2\epsilon \qquad (\gamma\epsilon \ll mc^2) \tag{8–7}$$

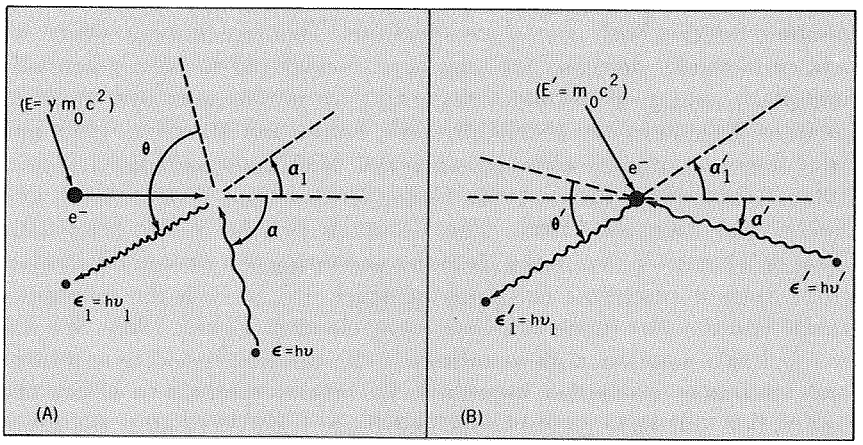

FIGURE 8–1.—A photon-electron collision, viewed in two reference frames (Felten, 1966). (*a*) Cosmic frame *S*. (*b*) Electron rest frame *S*′.

In the other extreme (Heitler, 1960) we must use the Klein-Nishina formula for the cross section, which has the asymptotic form

$$\sigma_c \to \pi r_0^2 \left(\frac{mc^2}{\epsilon}\right)\left[\frac{1}{2}+\ln\left(\frac{2\epsilon}{mc^2}\right)\right] \qquad (\gamma\epsilon \gg mc^2) \tag{8-8}$$

and we also find from equation (8–5) that

$$\epsilon_1 \sim \gamma mc^2 \sim E \qquad (\gamma\epsilon \gg mc^2) \tag{8-9}$$

Under the condition $\gamma\epsilon \ll mc^2$, the differential cross section for the production of a γ-ray of energy $E_\gamma = \epsilon_1$ by Compton scattering is given by (Ginzburg and Syrovatskii, 1964)

$$\sigma(E_\gamma|\epsilon, E) = \frac{\pi r_0^2}{4}\frac{(mc^2)^4}{\epsilon^2 E^3}\left\{2\frac{E_\gamma}{E} - \frac{(mc^2)^2 E_\gamma^2}{\epsilon E^3} + \frac{4E_\gamma}{E}\ln\frac{(mc^2)^2 E_\gamma}{4\epsilon E^2} + \frac{8\epsilon E}{(mc^2)^2}\right\} \tag{8-10}$$

and the mean energy of the γ-ray produced is given by

$$\langle E_\gamma\rangle = \frac{4}{3}\gamma^2\langle\epsilon\rangle \tag{8-11}$$

for an initial photon density distribution $n_{\rm ph}(\epsilon)$, where

$$\langle\epsilon\rangle = \frac{\int d\epsilon\, \epsilon\, n_{\rm ph}(\epsilon)}{\int d\epsilon\, n_{\rm ph}(\epsilon)} \tag{8-12}$$

The total γ-ray production spectrum is, of course, given by

$$I(E_\gamma) = \int d\mathbf{r} \int dE\, I_e(E, \mathbf{r}) \int dE\, n_{\rm ph}(\epsilon, \mathbf{r})\sigma(E_\gamma|\epsilon, E) \tag{8-13}$$

In the case where the cosmic-ray electrons have an energy distribution of the power-law form

$$I_e(\epsilon) = K_e E^{-\Gamma} \tag{8-14}$$

it is found that (Ginzburg and Syrovatskii, 1964)

$$\int dE\, I_e(E)\sigma(E_\gamma|\epsilon, E) = 2^\Gamma \frac{\Gamma^2+4\Gamma+11}{(\Gamma+1)(\Gamma+3)^2(\Gamma+5)} \times 8\pi r_0^2 K_e (mc^2)^{1-\Gamma}\epsilon^{(\Gamma-1)/2}E_\gamma^{(\Gamma+1)/2} \tag{8-15}$$

For the important case of interactions with the blackbody radiation, where

$$n_{\rm ph}(\epsilon) = \frac{8\pi}{h^3c^3}\frac{\epsilon^2}{e^{\epsilon/kT}-1} \tag{8-16}$$

we find that

$$\left\langle \frac{4}{3}\epsilon \right\rangle \simeq 3.6\ kT \simeq 3.1 \times 10^{-13} T \qquad \text{GeV} \tag{8-17}$$

The radiation density

$$\rho_\gamma = \int d\epsilon\ n_{\text{ph}}(\epsilon) \simeq 4.75 \times 10^{-12} T^4 \qquad \text{GeV/cm}^3 \tag{8-18}$$

and the expression (8–13) for the resultant γ-ray intensity reduces to

$$I(E_\gamma) = f(\Gamma)\,\frac{2}{3}\,\sigma_T L_{\text{eff}} \rho_\gamma (mc^2)^{1-\Gamma} \left(\frac{4}{3}\langle\epsilon\rangle\right)^{(\Gamma-3)/2} K_e E_\gamma^{-(\Gamma+1)/2} \tag{8-19}$$

which, in numerical form, becomes

$$I(E_\gamma) \simeq 6.22 \times 10^{-21} L_{\text{eff}} [10^{-2.962\Gamma} f(\Gamma)] K_e T^{(\Gamma+5)/2} E_\gamma^{-(\Gamma+1)/2} \qquad (\text{cm}^2\text{-s-sr-GeV})^{-1} \tag{8-20}$$

where L_{eff} is the effective pathlength for γ-ray production and

$$f(\Gamma) = 4.74(1.05)^\Gamma \frac{\Gamma^2 + 4\Gamma + 11}{(\Gamma+1)(\Gamma+3)^2(\Gamma+5)} \Gamma\left(\frac{\Gamma+5}{2}\right) \zeta\left(\frac{\Gamma+5}{2}\right) \tag{8-21}$$

$\Gamma(x)$ is the well-known gamma function and $\zeta(x)$ is the Riemann function

$$\zeta(x) = \sum_{n=1}^{\infty} \frac{1}{n^x} \tag{8-22}$$

In particular, Ginzburg and Syrovatskii give the values for $f(\Gamma)$ listed in table 8–1.

Thus, we find that for most applications of importance to high-energy astrophysics, where $2 \lesssim \Gamma \lesssim 3.5$, $f(\Gamma) \simeq 1$.

TABLE 8-1. —*Approximate Values of the Function* f(Γ) *in Equation (8–21)*

Γ	$f(\Gamma)$
1	0.84
2	.86
3	.99
4	1.4

As a check on equation (8–19), one can make the approximation for $\gamma\epsilon \ll mc^2$ that

$$\sigma(E_\gamma|\epsilon E) \simeq \sigma_T \delta\left(E_\gamma - \frac{4}{3}\langle\epsilon\rangle \frac{E^2}{(mc^2)^2}\right) \tag{8–23}$$

Then

$$I(E_\gamma) = n_{\rm ph}\sigma_T L_{\rm eff} \int dE\ K_e E^{-\Gamma} \delta\left(E_\gamma - \frac{4}{3}\langle\epsilon\rangle \frac{E^2}{(mc^2)^2}\right)$$

$$= n_{\rm ph}\sigma_T L_{\rm eff} K_e \left[\left(\frac{3}{4}\right)^{1/2} E_\gamma^{1/2} \langle\epsilon\rangle^{-1/2} mc^2\right]^{-\Gamma} \frac{dE}{dE_\gamma}$$

$$= \frac{1}{2}\, n_{\rm ph}\sigma_T L_{\rm eff} K_e (mc^2)^{1-\Gamma} \left(\frac{4}{3}\langle\epsilon\rangle\right)^{(\Gamma-1)/2} E_\gamma^{(\Gamma+1)/2}$$

$$= \frac{2}{3}\, \sigma_T L_{\rm eff} \rho_\gamma (mc^2)^{(1-\Gamma)} \left(\frac{4}{3}\langle\epsilon\rangle\right)^{(\Gamma-3)/2} K_e E_\gamma^{(\Gamma+1)/2} \tag{8–24}$$

which, for $f(\Gamma) \simeq 1$, is in excellent agreement with equation (8–19). The small numerical discrepancy between equations (8–19) and (8–24) arises because of the Bose-Einstein distribution in photon energies for a thermal photon field.

8–2 GAMMA-RAY PRODUCTION SPECTRA FROM BREMSSTRAHLUNG INTERACTIONS

Bremsstrahlung, which is a German word meaning "breaking radiation," is the radiation emitted by a charged particle accompanying deceleration. The cross sections for γ-ray production from bremsstrahlung are derived in Heitler's book (Heitler, 1960). In the case of bremsstrahlung from nonrelativistic electrons radiating in the field of a target nucleus, the cross section for production of a γ-ray of energy E_γ by an electron of energy E in the field of an atomic nucleus of charge Z is given by

$$\sigma_b(E_\gamma|E) \equiv \sigma_b(E, E_\gamma) f_b(E_\gamma|E) \tag{8–25}$$

where $f_b(E_\gamma|E)$ is again the normalized distribution function for γ-ray production; and where, in terms of kinetic energy $T = E - mc^2$,

$$\sigma_b(E, E_\gamma) = \frac{\alpha Z^2}{\pi}\, \sigma_T \left(\frac{mc^2}{T}\right) \ln\left\{\frac{[(T)^{1/2} + (T - E_\gamma)^{1/2}]^2}{E_\gamma}\right\} \left(\frac{T}{E_\gamma}\right)$$

$$\text{for } 2\pi Z\alpha \ll \beta \ll 1 \tag{8–26}$$

The cross section for bremsstrahlung by relativistic electrons is given by

$$\sigma_b(E, E_\gamma) = \frac{4\alpha Z^2}{\pi} \sigma_T \ln\left(\frac{2E}{mc^2} - \frac{1}{3}\right)\left(\frac{E}{E_\gamma}\right)$$

$$\text{for } mc^2 \ll E \ll \alpha^{-1} Z^{-1/3} mc^2 \qquad (8\text{–}27)$$

In the ultrarelativistic case, where the cross section is calculated by taking into account the screening of the charge of the atomic nucleus by atomic electrons, the resultant cross section is given by

$$\sigma_b(E, E_\gamma) = \frac{4\alpha Z^2}{\pi} \sigma_T \ln\left(183 Z^{-1/3} + \frac{1}{18}\right)\left(\frac{E}{E_\gamma}\right)$$

$$\text{for } E \gg \alpha^{-1} Z^{-1/3} mc^2 \qquad (8\text{–}28)$$

Of course, in the case of an ionized gas, equation (8–27), derived for the case where screening effects are unimportant, is applicable at all relativistic energies. The cross sections given in equations (8–26) to (8–28) may be corrected for the additional contribution from interactions between cosmic-ray electrons and atomic electrons by the replacement $Z^2 \rightarrow Z(Z+1)$.

Another case which may be of astrophysical interest for γ-ray production is that of bremsstrahlung from nonrelativistic protons, as has been pointed out by Boldt and Serlemitsos (1969). In this case, it is the electron which is at rest and the proton which is the energetic particle in the ls. The appropriate cross section for this interaction, which corresponds to equation (8–26) for cosmic-ray electrons, is then

$$\sigma_b(E_p, E_\gamma) = \frac{\alpha}{\pi} \sigma_T \left(\frac{M_p c^2}{T_p}\right)$$

$$\ln\left\{\frac{\left[\sqrt{(m_e/M_p)T_p} + \sqrt{(m_e/M_p)T_p - E_\gamma}\right]^2}{E_\gamma}\right\}\left[\frac{(m_e/M_p)T_p}{E_\gamma}\right] \qquad (8\text{–}29)$$

It is immediately obvious from equations (8–27) and (8–28) that for relativistic particles, the bremsstrahlung cross sections have little or no dependence, except for a linear one, on E. Indeed, equation (8–28) may be written in the form

$$\sigma_b(E, E_\gamma) \simeq \frac{\langle M \rangle}{\langle X \rangle}\left(\frac{E}{E_\gamma}\right) \qquad (8\text{–}30)$$

where $\langle M \rangle$ is the average mass of the target atoms in grams and $\langle X \rangle$ is the average radiation length for the gas in grams per square centi-

meter. The average radiation length for interstellar matter is

$$X \simeq 65 \text{ g/cm}^2 \tag{8-31}$$

based on the values given for pure hydrogen and pure helium by Dovshenko and Pomanskii (1964):

$$X_{\text{H}} = 62.8 \text{ g/cm}^2 \tag{8-32}$$

$$X_{\text{He}} = 93.1 \text{ g/cm}^2 \tag{8-33}$$

To a good approximation, especially in the case of relativistic bremsstrahlung (Heitler, 1960), the normalized distribution of γ-rays produced may be taken to be a square distribution given by

$$f(E_\gamma|E) \begin{cases} E^{-1} & \text{for } 0 \leq E_\gamma \leq E \\ 0 & \text{otherwise} \end{cases} \tag{8-34}$$

so that the γ-ray production spectrum is given by

$$I_b(E_\gamma) = \frac{\langle M \rangle}{\langle X \rangle} \left[\int_{E_\gamma}^{\infty} dE \, I_e(E) \right] E_\gamma^{-1}$$

$$= \frac{1}{\langle X \rangle} \int d\mathbf{r} \langle \rho(\mathbf{r}) \rangle \frac{I_e(>E_\gamma)}{E_\gamma} \tag{8-35}$$

where $\rho(\mathbf{r})$ is the matter density of the gas in grams per cubic centimeter. For bremsstrahlung between cosmic-ray electrons and interstellar gas, we may use equation (8–31) to write equation (8–35) in the form

$$I_b(E_\gamma) = 3.4 \times 10^{-26} \langle nL \rangle \frac{I(>E_\gamma)}{E_\gamma} \tag{8-36}$$

8–3 GAMMA-RAY PRODUCTION SPECTRA FROM SYNCHROTRON RADIATION

Synchrotron radiation, or magnetic bremsstrahlung, is the radiation emitted by a relativistic particle spiraling in a magnetic field. Its mathematical description has been given by Schwinger (1949). An electron suffers energy losses by synchrotron radiation at a rate

$$\left(\frac{dE}{dt} \right)_{\text{sync}} = -\frac{4}{3} \sigma_T c \gamma^2 \rho_H \tag{8-37}$$

where the magnetic energy density ρ_H is

$$\rho_H = H^2/8\pi \tag{8-38}$$

This rate can be compared with the energy loss rate suffered by an electron through Compton interactions with a photon field of energy density ρ_γ. That rate is

$$\left(\frac{dE}{dt}\right)_{\text{compt}} = -\frac{4}{3}\sigma_T c\gamma^2\rho_\gamma \tag{8-39}$$

The equivalence of equations (8–37) and (8–39) is not accidental, but can be shown to be a direct consequence of electromagnetic theory (Jones, 1965b).

The photons emitted as synchrotron radiation have a characteristic frequency given by

$$\omega_c = \frac{3}{2}\gamma^2\left(\frac{eH}{mc}\right) \tag{8-40}$$

The synchrotron effect can be thought of as the interaction of the electron with "virtual" photons of the magnetic field. Denoting these photons by the subscript v, it is found (Jones, 1968) that they have an average energy

$$\epsilon_v = \frac{8}{5\pi\sqrt{3}}\left(\frac{\hbar}{mc}\right)eH \tag{8-41}$$

and a number density

$$n_v = \frac{H^2}{8\pi\epsilon_v} \tag{8-42}$$

The resultant γ-rays have a characteristic energy found from equation (8–40) to be

$$E_{\gamma,c} = \frac{3}{2}\gamma^2\left(\frac{\hbar}{mc}\right)eH \tag{8-43}$$

Equation (8–43) expresses the same type of energy dependence on the electron energy, $E = \gamma mc^2$, as did equation (8–11) for Compton γ-rays. If we take a power-law spectrum of the form

$$I_e(E) = K_e E^{-\Gamma} \tag{8-44}$$

we will again get the same power-law dependence for the resultant synchrotron radiation as we did for the Compton radiation in the deriva-

tion of equation (8–24), viz,

$$I_{\text{sync}}(E_\gamma) \propto E_\gamma^{-(\Gamma+1)/2} \tag{8–45}$$

Ginzburg and Syrovatskii (1965) give the exact formula for $I_{\text{sync}}(E_\gamma)$ in a form suitable for calculation. The γ-ray spectrum, numerically modified from the form given by Ginzburg and Syrovatskii and expressed in gigaelectron volt units, is

$$I_{\text{sync}}(E_\gamma) = 9.46 \times 10^{-10}(8.15 \times 10^{-6})^{\Gamma} a(\Gamma) L_{\text{eff}} \times K_e H^{(\Gamma+1)/2} E^{-(\Gamma+1)/2} \quad (\text{cm}^{-2}\text{-s}^{-1}\text{-sr}^{-1}\text{-GeV}^{-1}) \tag{8–46}$$

with the coefficient $a(\Gamma)$ given by table 8–2.

A relativistic electron of energy E in gigaelectron volts, spiraling in a magnetic field of amplitude H, in gauss, will produce a characteristic spectrum of γ-rays having a peak at

$$E_{\gamma, m} = 1.9 \times 10^{-11} H_\perp E^2 \quad \text{GeV} \tag{8–47}$$

where $H_\perp$ is the component of the field perpendicular to the circular component of motion of the electron.

It follows from equation (8–47) that in a field of $H_\perp = 5 \times 10^{-6}$ G, which is of the order of the fields found in interstellar space, it takes a 10^8-GeV electron to produce a 1-GeV γ-ray. If we consider for comparison Compton interactions with starlight photons of roughly the same energy density and having energies of about 1 eV per photon, it only requires a 14-GeV electron to produce a 1-GeV γ-ray. Such electrons are at least 15 orders of magnitude more plentiful than are 10^8-GeV electrons, if indeed the latter exist at all; so it may readily be seen that for almost all cases of astrophysical interest at present, synchrotron radiation may be regarded as a negligible source of γ-rays.[1]

TABLE 8–2.—*The Coefficient* a(Γ) *in Equation (8–46)*

[Ginzburg and Syrovatskii, 1965]

Γ	$a(\Gamma)$
2.5	0.085
2.6	.083
3	.074
4	.072

[1] A possible important exception may be for point sources possessing strong magnetic fields, such as pulsars.

8–4 GAMMA RADIATION FROM PHOTOMESON PRODUCTION INTERACTIONS

We will mention here, in passing, the mechanism for production of γ-rays from the decay of neutral pions produced by interactions of ultra-high-energy cosmic rays; i.e., via interactions such as

$$\gamma + p \rightarrow p + \pi^0 \quad (8\text{–}48)$$
$$\pi^0 \rightarrow 2\gamma$$

where the threshold for interactions with starlight photons is of the order of 10^8 GeV. Hayakawa (1963) suggested that this interaction may be important for γ-ray production at energies above 10^6 GeV if the ultra-high-energy cosmic rays are universal. This is no longer thought to be the case, since, as we have seen in chapter 4, γ-rays of such energies cannot propagate more than 3×10^{22} cm, or about 3×10^{-6} of the visible radius of the universe, because of interactions with the universal blackbody radiation. In addition, there is considerable doubt as to the universality of ultra-high-energy cosmic rays (Stecker, 1968).

8–5 POSSIBLE IMPLICATIONS OF PRESENT OBSERVATIONS OF GALACTIC GAMMA RAYS

In this section, an attempt will be made to relate some of the theoretical calculations on galactic γ-ray production to the present observations and to thereby construct a plausible model for γ-ray production in our galaxy which is consistent with the present data. Unfortunately, it is necessary at this writing to preface this section with a caveat. We are now just on the threshold of establishing the field of observational γ-ray astronomy. It has become apparent that in order to detect diffuse fluxes of cosmic γ-rays above the atmospherically produced background, it is necessary to make use of satellite-borne detectors. Such detectors are just now at the stage of development where they have attained the sensitivity necessary for cosmic γ-ray detection. Instruments now in the development and planning stages will eventually provide a vast improvement in resolution and sensitivity. The data used here should be considered to be preliminary and subject to change. Thus, the interpretation of these data, as presented here, may require future modification.

We may mark the birth of observational γ-ray astronomy with the detection of cosmic γ-rays above 100-MeV energy by Clark, Kraushaar, and Garmire (1968). (See appendix.) Their results indicated that cosmic γ-radiation is strongly anisotropic, being most intense in the galactic plane and particularly at the galactic center. (See figs. 8–2 and 8–3.)

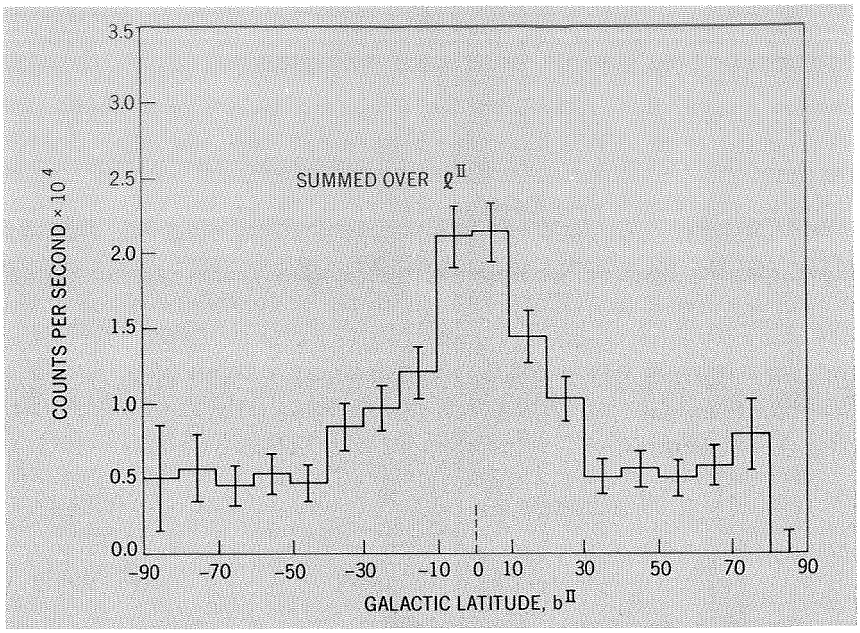

FIGURE 8–2. — Dependence of γ-ray intensity on galactic latitude b^{II} (data summed over all galactic longitudes l^{II}; Clark et al., 1969).

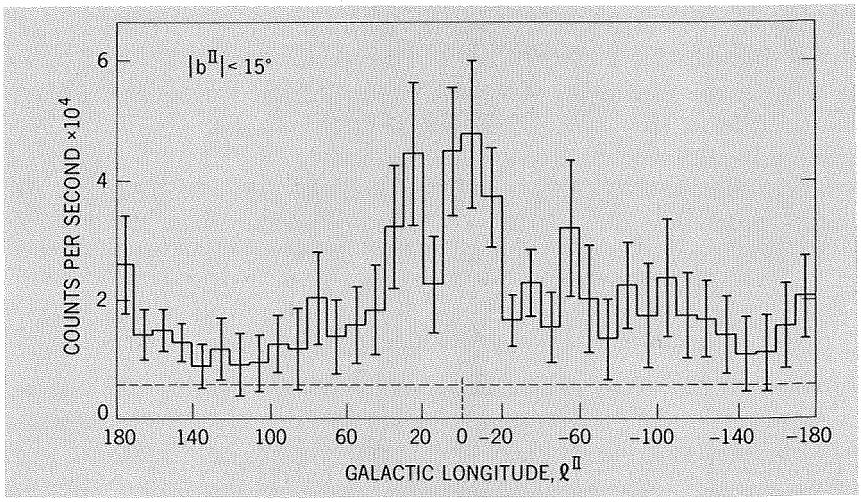

FIGURE 8–3. — Dependence of γ-ray intensity (within 15° galactic latitude of the galactic disk) on galactic longitude l^{II} (Clark et al., 1969).

The detection of this anisotropy itself is a strong indication that a large fraction of the γ-rays detected were of galactic origin. Fichtel, Kniffen, and Ögelman (1969) appear also to have detected the source at the galactic center. Sood (1969); Valdez, Frier, and Waddington (1969); and Hutchinson et al. (1969) have also reported an apparent anisotropy in detected γ-rays toward the galactic plane; although Frye et al. (1969) failed to detect such an anisotropy.

The absolute intensities of the γ-ray line source from the galactic plane and the peak in the intensity distribution at the galactic center remain somewhat in doubt (by probably not more than a factor of 2); and the intensities originally reported by Clark et al. (1968, 1969) have now been revised downward by approximately a factor of 2, due to a recalibration of the sensitivity of their detector (Clark et al., 1970). We shall utilize these revised intensities in our discussion in this section.

There appears to be a γ-ray flux from the galactic center above 100 MeV having a line intensity of $\sim 2 \times 10^{-4}$ cm^{-2}-s^{-1}-rad^{-1}. Gamma rays coming from the region of the galactic disk have a line intensity of 0.5×10^{-4} cm^{-2}-s^{-1}-rad^{-1}. Clark et al. suggested that these fluxes, first reported to be an order of magnitude higher than those predicted from various diffuse production mechanisms, may originate mainly in unresolved discrete sources (a suggestion which was further explored by Ögelman, 1969). However, they were careful to point out that large amounts of undetected hydrogen may also account for these fluxes.

From 21-cm radio observations of the galaxy, it has been found that the average value of the product of mean density and linear extension (usually denoted as $\langle nL \rangle$ for emitting atomic hydrogen in the galactic disk, spread out over the 15° resolution cone of the detector aboard the OSO–3 satellite is approximately 3×10^{21} cm^{-2}. This value corresponds to a mean density in the disk itself of approximately 0.7 cm^{-3} (Kerr and Westerhout, 1965). If the atomic hydrogen seen in emission were to be considered the full content of hydrogen gas in the galaxy, the resultant γ-ray production from π^0-decay, according to the results of chapter 5 (fig. 5–10), would produce a flux of γ-rays of energy greater than 100 MeV of $\sim 3 \times 10^{-5}$ cm^{-2}-s^{-1}-rad^{-1}, and the fluxes estimated from other production mechanisms in the galactic disk would be considerably lower.

The author (Stecker, 1969b) attempted to account for the fluxes originally reported by Clark et al. (1968) by suggesting that these γ-rays result from the decay of neutral pions produced in cosmic-ray interactions with the total nucleon content of interstellar gas, much of which was hypothesized to be in the form of molecular hydrogen. Arguments were given, based on recent results from other branches of astronomy dealing with the study of the interstellar medium, to support this hypothesis. This paper was closely followed by a detailed presentation of the OSO–3

results by Clark et al. (1969) at the 37th IAU Symposium in Rome showing that the γ-ray spectrum from the galactic disk closely matched that of the horizon-albedo γ-ray spectrum from the Earth, arising mainly from the decay of neutral pions produced by cosmic-ray interactions with the Earth's atmosphere. This gives tentative, but not conclusive, support to the pion-decay hypothesis for the origin of galactic γ-rays. Stronger support for the pion-decay hypothesis has recently been communicated by Fichtel and Kniffen (private communication) who have found that in the galactic-center region, $I(E_\gamma > 50\,\text{MeV}) < 1.5I\,(E_\gamma > 100$ MeV). (See also Kniffen and Fichtel (1970).)

To explain the γ-ray intensity originally quoted by Clark et al. (1968), using the pion-decay hypothesis, a mean gas density in the galactic disk of the order of 5 nucleons/cm^3 was required, a value close to the upper limit allowed by galactic dynamics (Parker, 1968). However, due to a recent recalibration of the sensitivity of the OSO–3 detector, the γ-ray fluxes originally given by Clark et al. (1968) have been revised downward by a factor of ~ 2 (Clark et al., 1970). A total nucleon density of the order of 2 cm^{-3} will provide a γ-ray flux in the galactic disk within the accuracy of the revised observational value under the assumption of a uniform cosmic-ray intensity in the galactic disk. Since 21-cm observations indicate a mean density of atomic hydrogen in the galactic disk of the order of 1 cm^{-3}, the γ-ray observations indicate that

$$\langle n_{\text{H-I, cool}} + 2n_{\text{H}_2} \rangle \simeq \langle n_{\text{H-I, emission}} \rangle \tag{8–49}$$

under the assumption of a fairly uniform cosmic-ray intensity in the galaxy.

A considerable quantity of molecular hydrogen in the interstellar medium had been considered a likely possibility until Stecher and Williams (1967) found an effective mechanism for its photodestruction. It now appears that in the presence of an average interstellar radiation field, the amount of molecular hydrogen expected to be present will be negligible. Recent rocket measurements appear to support this conclusion (Carruthers, 1968; Smith, 1969). In dark clouds, however, the rate of molecular hydrogen formation is expected to exceed the photodestruction rate; and essentially all the hydrogen is expected to exist in molecular form. Recent observations of dark clouds (Hollenbach and Salpeter, 1970, and Garzoli and Varsavsky, 1966) show an anticorrelation between atomic hydrogen and dust which may indicate that the hydrogen in these clouds has been converted into molecular form.

Kerr and Westerhout (1965) have argued that the hydrogen contained in cool, optically thick interstellar clouds can be expected to equal that seen in 21-cm emission, which is a more smoothly distributed component

of gas at a considerably higher temperature. Additional theoretical support for the model on the basis of dynamical stability arguments has also been given (Parker, 1968). In addition, the galactic longitude distribution obtained for interstellar hydrogen from 21-cm emission measurements alone appears to be far more isotropic than our concept of the Sun's position in the galaxy would indicate, which again suggests that a significant fraction of interstellar gas must be present in optically thick clouds within 10 kpc of the galactic center (Kerr and Westerhout, 1965). This argument is further strengthened by the fact that the gas-to-dust ratio in the interstellar medium appears to be constant, together with the observation of 27 magnitudes of extinction toward the galactic center (Becklin and Neugebauer, 1968) which implies that there is a large quantity of interstellar gas in that direction.

Gould and Salpeter (1963) and Gould, Gold, and Salpeter (1963) have pointed out that the observed spatial distribution of K-giant stars as a function of perpendicular distance from the galactic plane suggests a much stronger gravitational field for the galaxy than can be accounted for by stars and observed atomic hydrogen in the disk. A mean gas density of 5 cm^{-3} in the disk would be required to produce the observed K-giant distribution.

From an analysis of the observed distribution of atomic hydrogen gas and δ-Cephei variables, Dorschner, Gürtler, and Schmidt (1965) have come to the same conclusion, suggesting that 80 percent of the interstellar gas is in the form of molecular hydrogen. They show that the unseen mass necessary to produce the galactic gravitational field would have to be very strongly concentrated toward the galactic plane and therefore would not likely be composed of stars.

From studies of the spin temperature of interstellar hydrogen from 21-cm line spectra, Mebold (1969) has recently concluded that the total mass of interstellar hydrogen has been considerably underestimated from emission-line studies and that there exists a large quantity of gas which is in a condition favorable for star formation; viz, in the form of cool, dense clouds.

Werner and Harwit (1968) have observed a faint infrared emission feature which they have interpreted to be evidence for the existence of substantial amounts of molecular hydrogen in a dark cloud in Orion. The number of molecules along the line of sight is given as $\gtrsim 10^{21}$ cm^{-2}. Such clouds, although inherently difficult to observe, may be quite common in the galactic disk.

Since molecules such as NH_3, OH, H_2O, and CH_2O exist in detectable quantities, it would indeed be surprising if the H_2 molecule, made entirely of the most abundant element in the universe, did not exist in appreciable quantities. Indeed, Heiles (1968) has suggested that the

primary mechanism for the formation of OH molecules in dark clouds is based on the reaction

$$H_2 + O \rightarrow OH + H \qquad (8\text{–}50)$$

(Caroll and Salpeter, 1966) in which the H_2 molecule plays a fundamental role.

Studies of external galaxies have indicated that regions containing young stars (regions of active star formation) do not coincide in many cases with the regions of maximum atomic hydrogen density as seen in 21-cm emission. This would not be at all surprising if star formation occurred mainly in cool, dense, unobserved clouds, as suggested by Mebold (1969).

Most recently, Carruthers (1970) has made a direct observation of the H_2 Lyman resonance absorption bands in the far-ultraviolet spectrum of the star ξ Persei. His results indicate that, at least in this direction, nearly half of the total interstellar hydrogen exists in molecular form. Theoretical calculations by Hollenbach and Salpeter (*Astrophysical Journal*, in press) indicate approximately 100 percent efficiency for formation of molecular hydrogen on dust grains in neutral hydrogen (H-I) regions in the galaxy.

Thus, the pion-decay hypothesis for the origin of the disk component of galactic γ-radiation (under the assumption of a total mean nucleon density of interstellar gas of ~ 2 cm^{-3}) provides a natural and adequate explanation for both the intensity and spectral characteristics of this radiation as observed by Clark et al. (Stecher and Stecker, 1970). The intensity distribution of this component as a function of galactic longitude shows only one statistically significant peak; viz, the peak at the galactic center. Observations made by detectors with better sensitivity and resolution should enable γ-ray astronomers to map the disk component for γ-ray "hot spots," which should reflect the true distribution of the total content of interstellar gas, independent of temperature and optical opacity conditions in various regions of the galaxy. However, we are at present limited to a general discussion of the intensity of the disk component with the possibility of an additional source component at the galactic center. The peak in the γ-ray intensity at the galactic center, which has a line strength of $\sim 2 \times 10^{-4}$ cm^{-2}-s^{-1}-rad^{-1} above 100 MeV, as determined both by the revised OSO–3 measurements and by Fichtel et al. (1969) requires further discussion. Approximately half of these γ-rays can be explained as due to the decay of neutral pions produced in cosmic-ray interactions with the galactic gas (the disk component we have been discussing) on the assumption that the cosmic-ray intensity is uniform throughout the galaxy. An increase in cosmic-ray intensity

toward the galactic center by an additional factor of ~ 2 could thus account for the increased flux in the galactic center region. Alternatively we could introduce a "two-component" model for galactic γ-rays in which γ-rays from a production mechanism other than pion decay contribute an additional flux to that produced by the general disk component. We would thus classify the galactic center as a γ-ray source. There may be such a source of γ-rays produced by Compton interactions of cosmic-ray electrons with the intense infrared radiation field located at the galactic center and detected at 100μ by Hoffman and Frederick (1969). Hoffman and Frederick have found this source to extend $\lesssim 2°3'$ in galactic latitude and $\gtrsim 6°5'$ in galactic longitude and to have a brightness temperature of 16 K. The source has been suggested by Lequeux (1970) to be produced by reradiation of intense starlight in the central region of the galaxy by interstellar grains produced in the atmospheres of red giant stars (Donn et al., 1968), with such grains being an order of magnitude more numerous in the galactic center region than in the disk. Using the infrared intensities given by Hoffman and Frederick, we find that cosmic-ray electrons with the same spectrum as that observed at the Earth can produce a γ-ray flux of 2×10^{-5} to 7×10^{-5} $cm^{-2}\text{-}s^{-1}\text{-}rad^{-1}$ above 100 MeV by Compton interactions, which is the same order of magnitude as the estimated flux from the disk component in the galactic center region. A hypothetical γ-ray spectrum from the galactic center is shown in figure 8–4. It is impossible at this time to determine theoretically whether pion decay or Compton interactions would be expected to play the major role in the production of γ-rays at the galactic center under the assumptions of the two-component model presented here.[2] The situation is further complicated by the possibility of increased fluxes of both cosmic-ray electrons and nucleons at the galactic center, although there is no need to postulate the existence of such fluxes in order to account for the observed γ-radiation. It is also unnecessary to postulate the existence of an 8 K graybody infrared radiation field of galactic extent, a hypothesis which was invoked by Shen (1969) and Cowsik and Pal (1969) based on a measurement of Shivanandan, Houck, and Harwit (1968). In order to account for the originally quoted OSO–3 measurements, however, the proposed existence of this 13 eV/cm^3 radiation field poses serious theoretical problems pertaining to its origin and role in the galactic energy balance and its effect on cosmic-ray electrons (Anand, Daniel, and Stephens, 1969) and ultra-high-energy cosmic rays

[2] However, the recent measurements by Fichtel and Kniffen would appear to limit the Compton interaction flux to about 50 percent of the total flux from the galactic center above 100 MeV as in the model shown in figure 8–4.

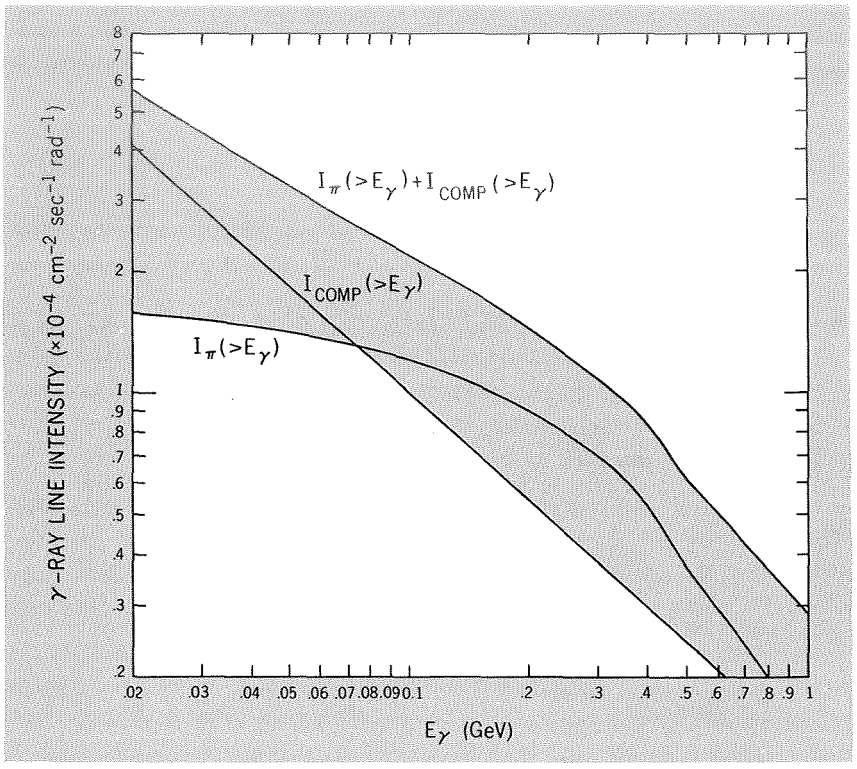

FIGURE 8–4. – A possible γ-ray spectrum from the galactic center based on the two-component source model (pion decay and Compton interactions), as discussed in the text.

(Encrenaz and Partridge, 1969).[3] The 8 K hypothesis is also in conflict with measurements of the spin temperatures of various molecules in the interstellar medium (Bartolot, Clauser, and Thaddeus, 1969; Thaddeus and Clauser, 1966; and Evans, Cheung, and Sloanaker, 1970) and most recently has been directly contradicted by a new infrared measurement by McNutt and Feldman (1970).[4]

Based on the discussion we have just presented, Stecher and Stecker (1970) reached some tentative conclusions regarding the origin of galactic γ-rays.

(1) Gamma rays originating in the galactic disk most likely result from the decay of neutral pions produced in interstellar cosmic-ray

[3] It has also recently been found to conflict with measured upper limits of hard X-ray emission from the galactic plane (Blecker and Deerenberg, 1970).

[4] Shivanandan (1970) has reported that due to a recent recalibration of their detector, the flux originally reported by Shivanandan et al. (1968) should be reduced by a factor of ~ 4 and that the revised flux should be considered an upper limit.

interactions. The excess originating in the galactic center region can be produced by a combination of the pion-decay process and Compton interactions between cosmic-ray electrons and infrared radiation.

(2) The explanations offered above obviate the necessity for invoking strong γ-ray point sources, large gradients in the galactic cosmic-ray flux, or 8 K graybody radiation fields of galactic extent in order to explain the revised γ-ray observations.

8-6 POSITRON-ANNIHILATION GAMMA RAYS AT 0.51 MeV FROM THE GALACTIC PLANE AND THE GALACTIC CENTER

We have seen in chapter 7 that positrons annihilate primarily from an S-state of positronium, with 75 percent of these annihilations producing a three-photon continuum rather than a two-photon line at 0.51 MeV. Therefore, on the average, one 0.51-MeV photon is produced for every two positrons which annihilate. Thus, the intensity of 0.51-MeV γ-rays observed along the line of sight as a function of galactic coordinates is given by

$$I_{0.51}(l^{\text{II}}, b^{\text{II}}) = \frac{Q_{T,\,\text{rest}} M(l^{\text{II}}, b^{\text{II}})}{8\pi} \tag{8-51}$$

where $M(l^{\text{II}}, b^{\text{II}})$ in grams per square centimeter is the amount of interstellar gas in the direction of observation. The resultant γ-ray intensities for various directions of observation are given in table 8–3. The values of $M(l^{\text{II}}, b^{\text{II}})$ obtained from 21-cm observations are taken from Ginzburg and Syrovatskii (1964). The values of $M(l^{\text{II}}, b^{\text{II}})$ designated by "missing-mass hypothesis" are based on the discussion of the last section, as needed to explain the recent observations of 100-MeV γ-rays from the galaxy as being due to bremsstrahlung and π° production.

The results of Metzger et al. (1964) indicate that the background continuum X-rays have a flux of about 6×10^{-5} cm^{-2}-s^{-1}-sr^{-1}-keV^{-1} at 0.51 MeV. Thus, an instrument with a resolution of 5 keV (the predicted width of the 0.51-MeV line) would be able to measure a line imposed on that continuum with a flux of about 3×10^{-4} cm^{-2}-s^{-1}-sr^{-1}.

Thus, $I_{0.51}(l^{\text{II}}, b^{\text{II}})$ must be greater than 3×10^{-4} cm^{-2}-sr^{-1}-s^{-1} in order to be observable above the X-ray background continuum by a detector with an energy resolution of 5 keV, which is the theoretical width of the 0.51-MeV line. This intensity is therefore a reasonable lower limit on the 0.51-MeV line intensity, which must be present in order for the annihilation line to be detected. By comparing this lower limit with the calculated intensities given in table 8–3, we see that the annihilation radiation could only be detected in the direction of the galactic center,

TABLE 8–3.—*Resultant γ-Ray Intensities for Various Directions of Observation*

	Solar minimum	$R_r = 350$ MV		Power law		$I_+ = 2\times10^{-2}$ cm^{-2}-s^{-1}-sr^{-1}	
		$R_0 = 500$ MV	$R_0 = 200$ MV	$T_c = 100$ MeV/ Nucleon	$T_c = 5$ MeV/ Nucleon	Mean	Maximum
Average (including halo) (21-cm) $\frac{1}{4\pi}\int dl^{II}\sin b^{II} db^{II} M(l^{II}, b^{II}) \simeq 1.6\times10^{-3}$	7.0×10^{-8}	1.1×10^{-7}	2.8×10^{-6}	2.1×10^{-6}	8.3×10^{-6}	$\frac{1.4\times10^{-6}}{n^{5/2}}$	3.2×10^{-5}
Anticenter (21-cm) $M(\pi, 0)\simeq 1.2\times10^{-2}$	5.6×10^{-7}	8.6×10^{-7}	2.1×10^{-5}	1.6×10^{-5}	6.2×10^{-5}	$\frac{1.0\times10^{-5}}{n^{5/2}}$	2.4×10^{-4}
Galactic center (21-cm) $M(0,0)\simeq 6\times10^{-2}$	2.7×10^{-6}	4.3×10^{-6}	1.0×10^{-4}	7.9×10^{-5}	3.1×10^{-4}	$\frac{5.3\times10^{-5}}{n^{5/2}}$	1.2×10^{-3}
Disk average (missing-mass hypothesis) $\frac{1}{2\pi}\int dl^{II} M(l^{II}, 0) \simeq 3\times10^{-2}$	1.4×10^{-6}	2.2×10^{-6}	5.0×10^{-5}	4.0×10^{-5}	1.6×10^{-4}	$\frac{2.7\times10^{-5}}{n^{5/2}}$	6.0×10^{-4}
Galactic center (missing-mass hypothesis) $M(0, 0) \simeq 0.1$	4.4×10^{-6}	7.0×10^{-6}	1.7×10^{-4}	1.3×10^{-4}	5.0×10^{-4}	$\frac{8.5\times10^{-5}}{n^{5/2}}$	2×10^{-3}

and, with the "missing-mass hypothesis," possibly also as a disk average. The calculated γ-ray fluxes, however, were obtained by assuming that the primary cosmic-ray intensities are spread uniformly along the line of sight over which the annihilation is formed. Such an assumption requires a mean cosmic-ray energy density of ~ 50 eV/cm^3 in order to produce a detectable annihilation line for the demodulated cosmic-ray spectrum with $R_r = 350$ MV and $R_0 = 200$ MV and for the power-law distribution. This energy density is at least an order of magnitude higher than that allowed by the general dynamics of the interstellar medium (Parker, 1966). The energy requirements for the power-law spectrum with $T_c = 100$ MeV/nucleon are smaller and therefore not necessarily inconsistent with the energy arguments mentioned above. A primary cosmic-ray spectrum of this form, however, conflicts with the ^{2}H and ^{3}He calculations (Ramaty and Lingenfelter, 1969) and possibly with the positron measurements in the 10 to 10^3 MeV region. (See fig. 7–5.) Therefore, it is probably not a good representation of the overall galactic cosmic-ray distribution.

We conclude that the 0.51-MeV annihilation γ-ray intensity produced by positrons from both pion and CNO beta emitters for a homogeneous disk model most probably will be smaller than the observed X-ray background and hence be unobservable.

As can be seen from table 8–3, however, if the 1-MeV positron measurement of Cline and Hones (1969) is regarded as a real flux rather than as an upper limit and is spread uniformly along the line of sight, the annihilation line would be observable both toward the galactic center and as a disk average. However, if these 1-MeV positrons are produced in supernova explosions and exhibit spatial and temporal inhomogeneities corresponding to their short ranges, the resultant γ-ray flux would again be below the X-ray background and would be unobservable.

Since the galactic center is known to be an intense source of high-energy γ-rays, and since the energy arguments that we have used do not necessarily hold for that region, the galactic center may be a detectable source of 0.51-MeV γ-rays. It may thus be more profitable to look for this radiation with a high-spatial-resolution detector than to look for a diffuse galactic flux. This argument is valid even if a diffuse flux is detectable, since, as can be seen from table 8–3, such a flux would still be more intense toward the galactic center.